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Crack Detectability and Durability of Coaxial Cable Sensors in Reinforced Concrete Bridge Applications

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The working mechanism and the measurement principle of topology-based crack sensors made of coaxial cables are briefly reviewed. The sensitivity, spatial resolution, and ruggedness of two coaxial cable sensors, respectively made of rubber and Teflon dielectric materials, were compared and validated with laboratory testing of a ⅘-scale, T-shaped, reinforced concrete beam-column specimen. Two Teflon sensors were installed on one of the solid decks of a three-span continuous highway bridge to investigate their durability and measurement repeatability. Laboratory tests indicated that both types of sensors have high sensitivity, but the Teflon sensor has a higher spatial resolution and a negligible spillover effect of any significant cracks. At a 90-degree bend, however, the Teflon sensor is more susceptible than the rubber sensor to the rubbing action of the outer conductor of a coaxial cable against its dielectric layer. No cracks were observed during the field load tests of the instrumented bridge. Both sensors indicated high durability in real-world application but a certain variation of waveforms was measured over a period of 5 years because of the use of different instruments. Future research is directed to develop an online calibration of crack sensors with a small portion of built-in standard cable at the end of the cable sensor.

Cracks in reinforced concrete bridge structures often lead to structural degradation because of reinforcement corrosion associated with water leakage and chloride invasion, particularly in maritime environments. In terms of structural capacity, the crack width of engineering concern is approximately 0.013 in. (0.33 mm) for interior exposure or 0.016 in. (0.41 mm) for exterior exposure. In the case of nuclear reactors or other waste solid treatment plants, however, this limit would be much smaller to prevent any leakage of hazardous materials. However, a cracked structure can still support significantly more loads before it becomes unstable. Therefore, the crack width of engineering significance covers a wide range, making detecting cracks with embedded sensors a challenging task.

Coaxial cables as sensors have found many applications in geomechanics since the 1970s (*1*). Two parallel cables have also been applied to detect corrosion in steel cables by using a twin-conductor transmission line (*2*). For crack detection in structures, however, the traditional cables designed on the basis of the change in geometry (*3*) are not sensitive. The recent introduction of the topology-based design concept enabled the use of coaxial cable sensors for crack detection in structures (*4*). Unlike the geometry-based design concept, the topology-based concept was focused on the longitudinal strain effect when a cable sensor is embedded in concrete. In this study, coaxial cable sensors are further investigated and validated in large- and full-scale reinforced concrete bridge structure applications.

COAXIAL CABLE SENSORS

Two designs of cable sensors were developed on the basis of the change in topology or electrical structure of coaxial cables. These designs are shown schematically in Figure 1. The first sensor, the rubber sensor, was custom designed with a dielectric rubber tube around which a copper tape with adhesives is spirally wrapped as the outer conductor of the cable to facilitate the change of the electrical structure under strain conditions (*4*). The second sensor, the Teflon sensor, was custom designed with a Teflon dielectric layer and a steel spiral that can slide along the Teflon surface under strain conditions (*5*). A key factor in their fabrication is to ensure that any two adjacent spirals are electrically in contact but separate easily under strain effects.

A coaxial cable is used as a sensor and a signal carrier in electrical time-domain reflectometry (ETDR) measurements as shown in Figure 2*a.* An ETDR sampling head launches a series of low-amplitude and fast-rising step pulses onto the cable and samples the reflected electromagnetic wave caused by an electrical property change or a discontinuity along the cable. The arrival time of the reflected signal represents the distance from the point of monitoring to the discontinuity, and the intensity of the signal represents the degree of the discontinuity. A cable sensor embedded in concrete can thus detect both the location and the width of a crack simultaneously.

On the outer conductor of a coaxial cable, the presence of a partial or complete separation between adjacent spirals will force the return current on the transmission line outer shield to change its flow path, as shown in Figure 2*b.* This effect introduces an added inductance, according to the transmission line theory (*6*). A portion of the incident wave will therefore be reflected when it encounters this discontinuity.

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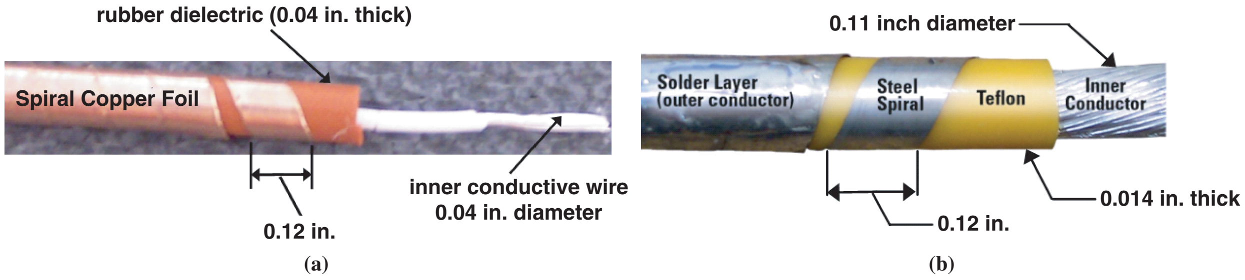


FIGURE 1 Two custom-made prototype coaxial cables: (*a*) rubber sensor and (*b*) Teflon sensor.

PERFORMANCE FOR DETECTION OF FLEXURAL CRACKS

To compare their performance, two prototypes of sensors as shown in Figure 1 (approximately 12 in. apart and symmetric about the loading plane) were installed on a ⅕-scale, reinforced concrete beam-column specimen as shown in Figure 3*a*. The specimen was designed to reproduce the behavior of a critical portion of a highway bridge under simulated seismic loads. The circular column of the specimen is 24 in. (610 mm) in diameter. It is reinforced with 14 No. 9 longitudinal bars and No. 4 hoops at 9⅝-in. (245-mm) spacing. The rectangular bent cap has a cross section of 3 ft 6 in. by 2 ft 10½ in. (740 mm by 880 mm) and is reinforced with 5 No. 8 bars at the top and 10 No. 8 bars at the bottom, as well as No. 5 stirrups every 7¼ in. (184 mm). The specimen was loaded laterally against the reaction wall with a progressively increasing, fully reversed force in the elastic range (at three levels of 19.43, 38.85, and 58.28 kips) and then an increasing displacement in the inelastic range (*7*). The thin-sheet steel wrapping and the X-shaped steel cage (Figure 3*a*) were installed to increase the seismic strength and ductility of the specimen after the elastic tests were completed (*7*).

Cracks developed in the column and were detected by both sensors. At the applied load of 58.28 kips, five flexural cracks were observed on either side of the loading plane as shown in Figure 3*b*. A comparison of how the sensors responded to the increased crack widths is made in Figures 4 and 5, in which the horizontal axis represents the distance along the sensor from the top of the column and the vertical axis shows the reflection coefficient, indicating how strong the reflected waves are by measuring the multiple cracks. Considering a noise reflection coefficient of approximately 3 millirho (mrho) (*4, 5*), Figures 4 and 5 show that all five cracks on the column were clearly detected by the rubber sensor, whereas the first four were identified by the Teflon sensor at the load of 58.28 kips (red line in Figures 4 and 5). At the increased loading level, both sensors clearly detected all cracks on the column, including two additional cracks intercepting the rubber sensor at the top of the column as illustrated above the retrofitting scheme in Figure 3*a.* In addition, the rubber sensor also detected one crack at the top of the beam, which was confirmed by the physical observation during testing.

Figures 4 and 5 also show that both sensors have similar sensitivity under pseudostatic loading even though the rubber sensor is nearly insensitive to cracks under dynamic loads (*5*). This effect may be caused either by the use of a smaller diameter in the rubber sensor or by the higher turn density of the copper spiral in the rubber sensor (*4*). However, the spatial resolution of the rubber sensor is lower, as a result of measuring wider wave bandwidths, because the deformation in rubber, facilitating the separation of the outer conductor, is spread over a larger distance than the local separation in the Teflon sensor. In addition, the spillover effect of the rubber sensor from any appreciable crack to the remaining part of the cable sensor is significant. In other words, the reflection curve has been shifted upward as the load increases. For example, for the beam portion, the two reflection curves at loads of 38.85 kips and 58.28 kips are nearly parallel, and the reflection coefficient at 58.28 kips is significantly higher even though no crack was observed. This phenomenon was due to the deformation effect of the rubber dielectric layer of the rubber sensor around the 90-degree bend at the beam–column construction joint.

At a load displacement of 1.17 in. (30 mm), the Teflon sensor lost its signal at the construction joint as indicated in Figure 5, but the rubber sensor seemed unaffected. This difference was attributed to the characteristics of the two sensor types. The rubber sensor was constructed with rubber dielectric and therefore was more flexible

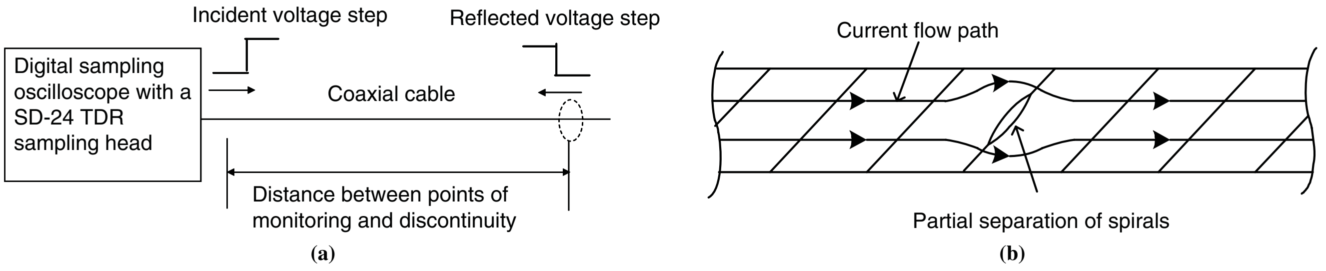
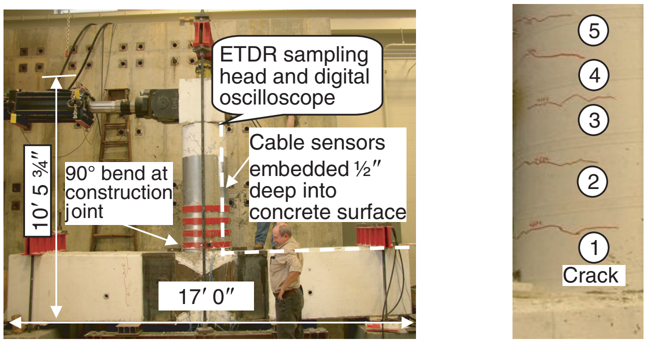


FIGURE 2 Coaxial cable as one distributed crack sensor: (*a*) measurement principle and (*b*) sensing mechanism.



(a) (b)

FIGURE 3 View of ⅘-scale test specimen: (*a*) ⅘-scale specimen and (*b*) flexural cracks at 58.28 kips.

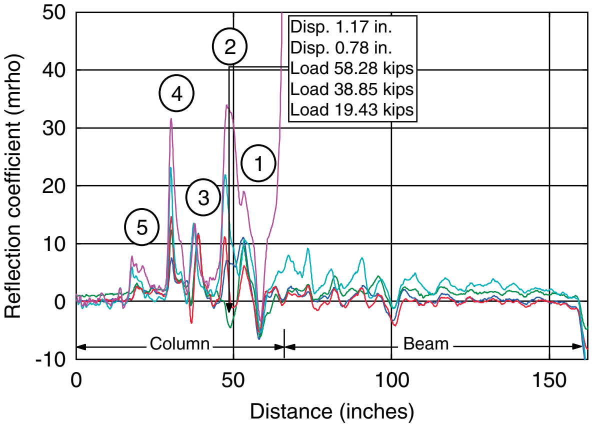


FIGURE 5 Differenced signal from Teflon sensor.

than the Teflon sensor, which was constructed with Teflon dielectric. As shown in Figure 1*b,* the outer conductor of a Teflon sensor is typically made of steel spirals that are soldered outside. At the 90-degree transition bend from the column to the beam, however, the outer conductor of the Teflon sensor consisted of a copper foil tape that was carefully wrapped around the dielectric material and soldered to the stainless steel spiral materials in the straight portion of the Teflon sensor. This copper foil had essentially been peeled off the dielectric, which physically and electrically separated the beam portion of the sensor from the measured end. The repeated bending of the sensor and scraping action of the concrete against the foil during cyclic loading had slowly scraped the foil from the sensor. Figure 6 shows the bare Teflon portion of the sensor at the open construction joint and also shows that the rubber sensor seems to have only stretched. The stretching of the rubber sensor is what enables that particular sensor to survive such a brutal action. The results of this test show that for application purposes, a 90-degree bend of a Teflon sensor at a construction joint is not recommended. However, the rubber sensor performed well even with a large displacement at the construction joint.

Figure 7 presents the relationship between the peak reflection coefficient and the strain of a reinforcing bar close to the cable sensors. As can be seen, the rubber sensor gives a higher slope of the reflection–strain curve. For the case of the Teflon sensor, the reflection–strain is nearly linear when the column's behavior is within elastic range.

DURABILITY AND REPEATABILITY IN FIELD APPLICATIONS

To ensure the durability of coaxial cables in field applications and the consistency of field measurements, two Teflon sensors were installed in Bridge P-962 located in Dallas County, Missouri. The sensors were grouted in the transverse direction into the bottom of the bridge deck in October 2003 and since then have been tested every 6 months for a period of 5 years. The bridge is a three-span, continuous concrete bridge with three longitudinal reinforced concrete girders (Figure 8*a*). The location of the ½-in. (12.5-mm) deep embedded sensors can be seen in Figure 8*b*.

The main objective of the load tests was to understand the load capacity of the strengthened bridge and its potential change over

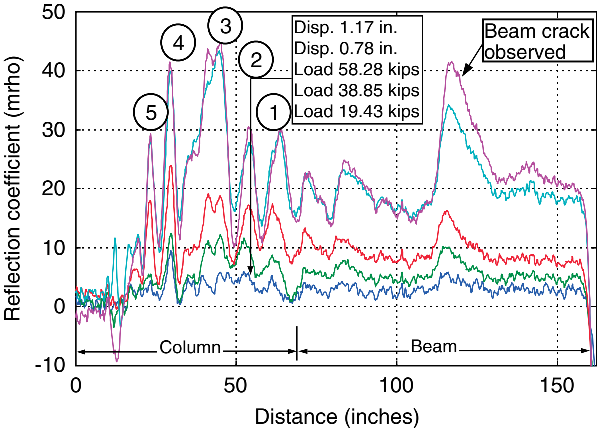


FIGURE 4 Differenced signal from rubber sensor.

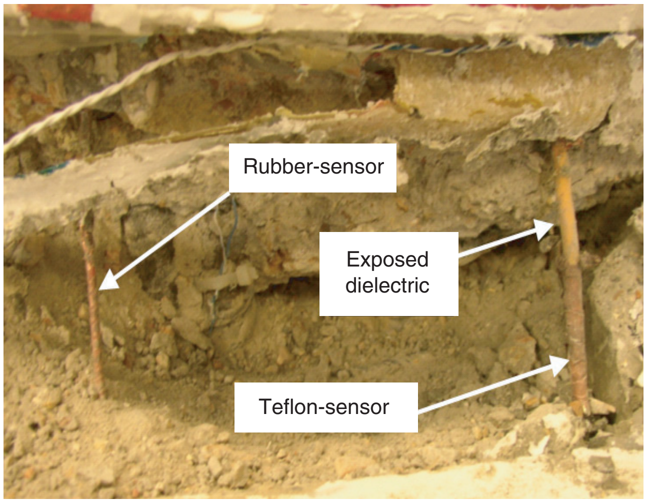


FIGURE 6 Exposed sensors at construction joint.

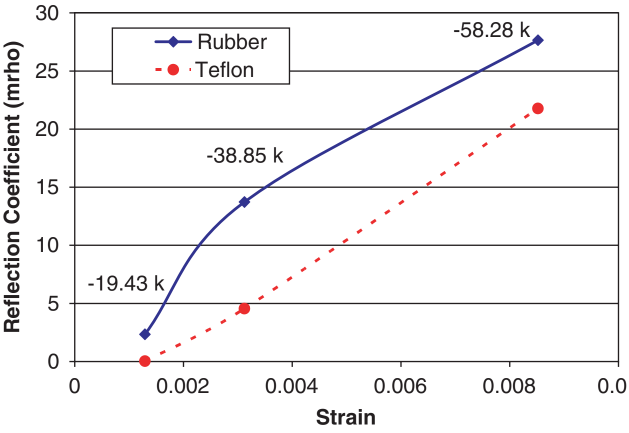


FIGURE 7 Crack sensor data versus strain data.

5 years from environmental effects (*8*). At the design load, no cracks were found in the bridge deck. Therefore, the focus of the load tests was then to monitor any strain effects present in the bridge due to traffic loads. The load tests were performed by using two Missouri Department of Transportation trucks filled with gravel. For two load cases, the ETDR signals were recorded. For Load Case I, the trucks were parked back to back in the center of the first span on the side opposite the sensor location. Load Case II involved the trucks parked back to back in the center of the first span and in the center of the bridge deck. The differenced signals from the two load cases can be seen in Figure 9 from Sensor 1.

Figure 9 shows that little change has occurred in all the sensor signals except for the April 2006 measurements. Visual inspections during the April 2006 load test showed no visible cracks under the bridge deck (*9*). The fluctuation of the April 2006 waveform was likely due to a loose connection at the beginning of the sensor. Overall, the sensor gave consistent readings within 5 years; the indication of no crack is consistent with visual inspections. Nevertheless, the difference in various waveforms for long-term monitoring may necessitate the development of an online calibration technology by introducing a small portion of standard design cable at the end of each cable sensor. This reference portion of the cable will not change with any cracking in concrete but records any long-term drift of signals in exactly the same way as the crack sensor does. In this case, the long-term drift effect can be removed from the measured signals from the crack sensor.

Sensor 2 was damaged at one end during the May 2005 and October 2005 load tests. A portion of grout near the connection of Sensor 2 fell away, exposing part of the sensor, as seen in Figure 10. The exposed part of the sensor shows some discoloration and corrosion. The exposed portion of the sensor was first noted during the May 2004 tests, but the sensor still gave a good signal. This problem likely occurred from the pulling of connection cables during the setup of one load test. The issue was corrected during the April 2006 tests by connecting the ETDR head to a connector on the other end of the sensor.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the experimental tests in laboratory and field conditions, the following conclusions can be drawn:

- Under pseudostatic loading, both rubber and Teflon sensors are sensitive to cracking and capable of detecting the location of cracks. However, rubber sensors have a lower spatial resolution with significant spillover effects due to the 90-degree bend at the beam–column construction joint.
- Rubber sensors can withstand many cycles of rubbing and pulling on their outer conductors or spiral wrapping because of the flexibility of their dielectric layers. It is preferable not to use a 90-degree bend for a Teflon sensor when it is subjected to cyclic loading.
- Topology-based cable sensors generally give consistent results in laboratory and field conditions. They are extremely rugged and durable for long-term monitoring.
- Performance validation studies with testing of the large-scale specimen or real-world bridge structure indicated that coaxial cable sensors are especially applicable in inaccessible areas such as pile and shaft foundations, columns wrapped with strengthening materials, massive concrete structures, and structures that are covered with architectural features and fireproofing furnishings.

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(a) (b)

FIGURE 8 Sensor implementation on bridge in Dallas County, Missouri: (*a*) overview and (*b*) installed sensors.

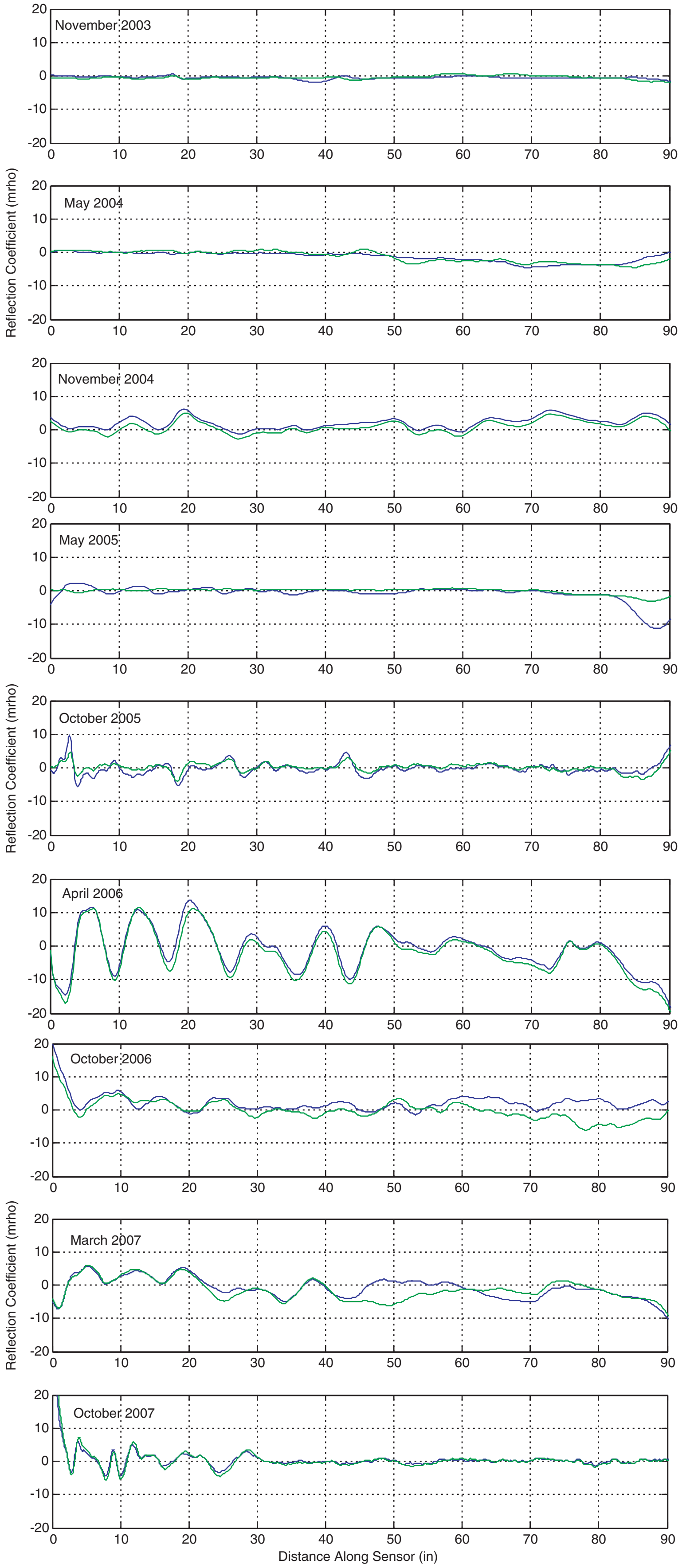

FIGURE 9 Reflection coefficient waveforms over 5 years.

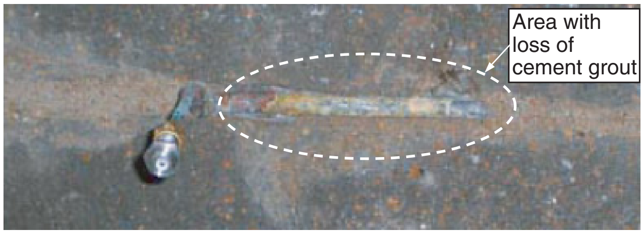

FIGURE 10 Exposed end of coaxial cable sensor on bridge.

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